Determining soil engineering parameters from CPT data

NCHRP
SYNTHESIS 368

Cone Penetration Testing

A Synthesis of Highway Practice

TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMIES

Downloads available at: (http://10.160.173.166/GRG/research_themes/geo-implementation/data-int/cpt/cpt_main.htm)

1. CPT Previewer documentation
2. CPT data to XML conversion documentation
3. Vertek CPT Processing Software
4. Hogentogler CPT Processing Software
5. 10 Recommended Articles
6. Axial capacity of driven piles
7. Louisiana Pile_CPT22
8. Performance evaluation of pile foundation using CPT
10. Pile bearing capacity prediction
11. Pile foundations for large north sea structures
12. SBT and Fines (excel spreadsheet)
13. Soil classification using the CPT
14. US National Report on CPT
15. Use of CPTu to Estimate Equivalent SPT N60
16. CPT Soil Property Interpretation
17. CPT Liquefaction
18. CPT_interpretation (excel spreadsheet)
19. CPT_liquefaction Analysis (excel spreadsheet)

"As with conventional practice, soils are grouped into either clays or sands, in particular referring to "vanilla" clays and "hourglass" sands."

Non-textbook geomaterials that require site-specific validation of these relationships include:
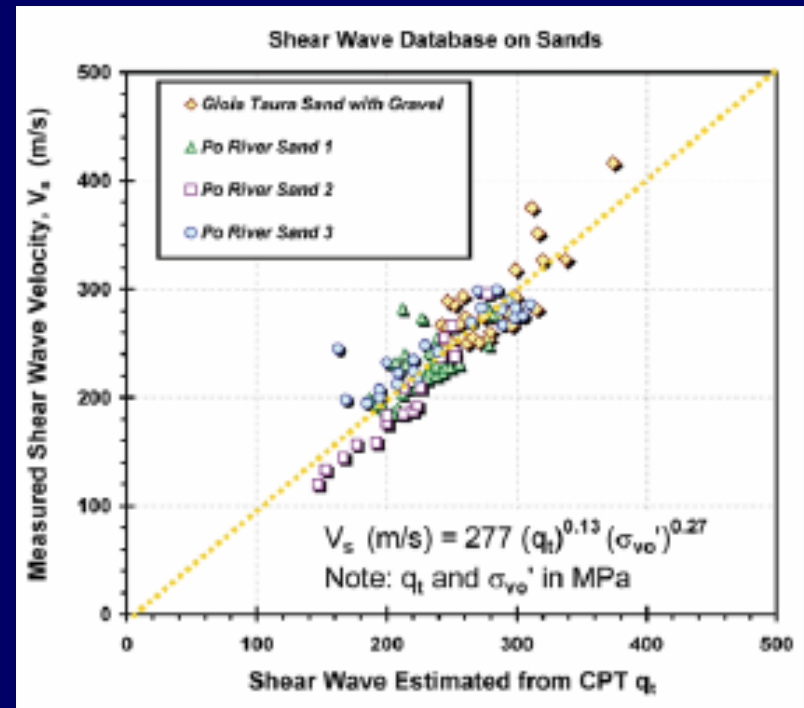
- Cemented sands
- Carbonate sands
- Sensitive clays
- Residual and tropical clays
- Glacial till
- Dispersive clays
- Collapsible soils

Correlations to the following engineering parameters are presented:

1. Shear wave velocity
2. Unit weight
3. Small strain shear modulus
4. Soil stiffness
5. Stress history – preconsolidation stress
6. Effective stress strength (ϕ')
7. Undrained shear strength of clays
8. Sensitivity
9. Relative density of clean sands
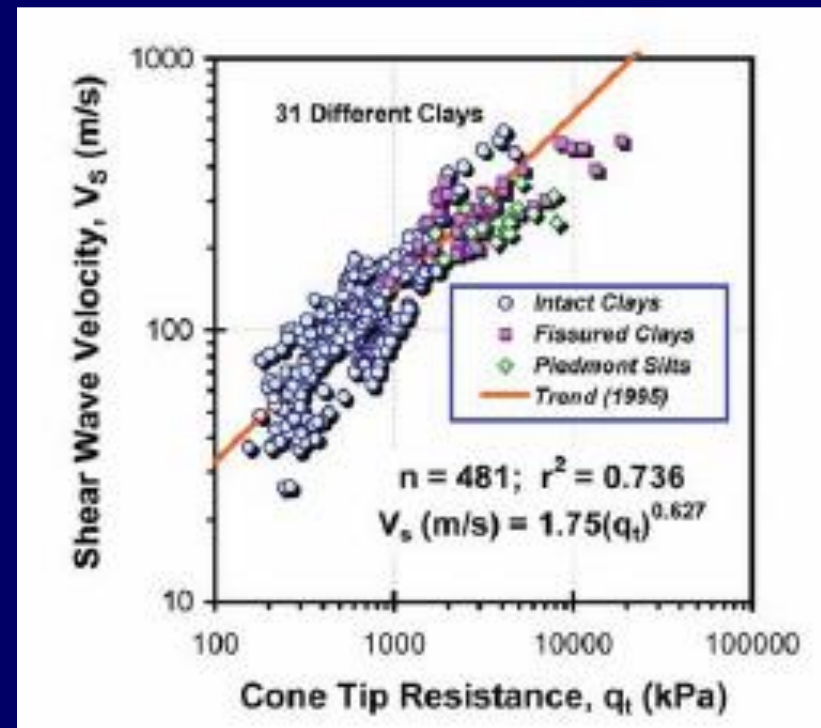10. Coefficient of consolidation
11. Rigidity index

Shear wave velocity estimate (Baldi, 1989)

- For uncemented, unaged quartizitc sands:
  - $V_s = 277 \, (q_t)^{0.13} \, (\sigma_{v0}')^{0.27}$
    - V_s is in m/s
    - q_t and σ_{v0}' are in units of MPa

Shear Wave Database on Sands

V_s (m/s) = $277 \, (q_t)^{0.13} \, (\sigma_{v0}')^{0.27}$
Note: q_t and σ_{v0}' in MPa

Shear wave velocity estimate (Mayne and Rix, 1995)

- For soft to firm to stiff intact clays and fissured clays:
  - $V_s = 1.75\,(q_t)^{0.627}$
    - V_s is in units of m/s
    - q_t is in units of kPa

31 Different Clays

- Intact Clays
- Fissured Clays
- Piedmont Silts
- Trend (1995)

$n = 481; \ r^2 = 0.736$

$V_s\,(m/s) = 1.75(q_t)^{0.627}$

Shear Wave Velocity, V_s (m/s)

Cone Tip Resistance, q_t (kPa)

Shear wave velocity estimation methods (Hegazy and Mayne, 1995)

- For all soil types:
  - $V_s = ((10.1)(\log q_t) - 11.4))^{1.67}((f_s/q_t)(100))^{0.3}$
    - V_s is in m/s
    - q_t and f_s are in units of kPa

- For all saturated soils:
  - $V_s = (118.8)(\log f_s) + 18.5$
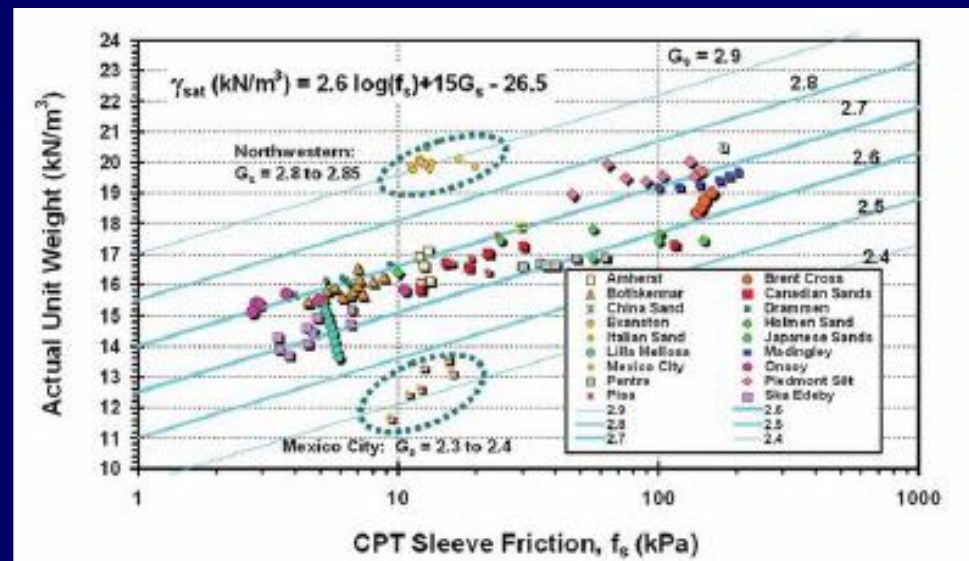   - V_s is in units of m/s
    - f_s is in units of kPa

Estimating the unit weight of saturated soils with shear wave velocity measurements

- $\gamma_T = 8.32 \, (\log V_s) - (1.61) \, (\log z)$
  - γ_T is in units of kN/m^3 (1kN/m^3 = 6.366 lb/ft^3)
 - V_s is in units of m/s
  - z is depth, in units of meters
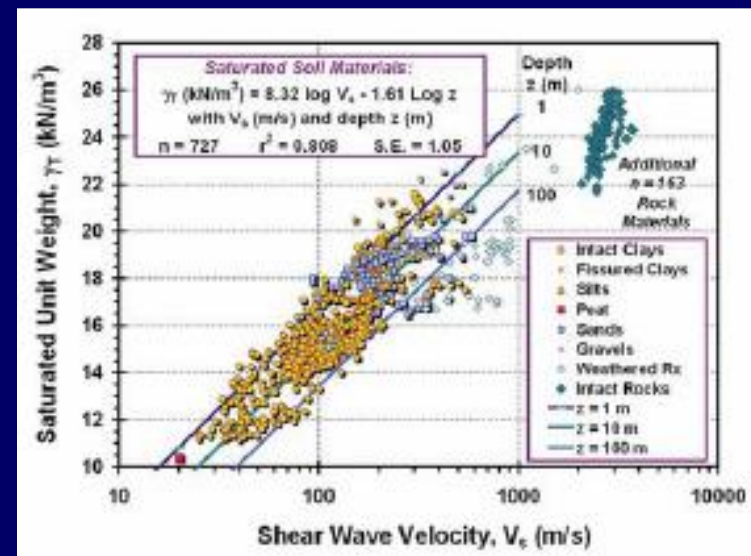
Estimating the unit weight of saturated soils with CPT friction sleeve measurements

- $\gamma_{sat} = 2.6\ (\log f_s) + 15\ (G_s) - 26.5$
  - γ_{sat} is in units of kN/m^3 $(1 kN/m^3 = 6.366\ lb/ft^3)$
  - f_s is in units of kPa
- If G_s is assumed to be 2.65, the equation becomes:
  - $\gamma_{sat} = 2.6\ (\log f_s) + 13.25$

Estimating the small strain shear modulus (G_0 or G_{max}) with shear wave velocity measurements and the soil unit weight
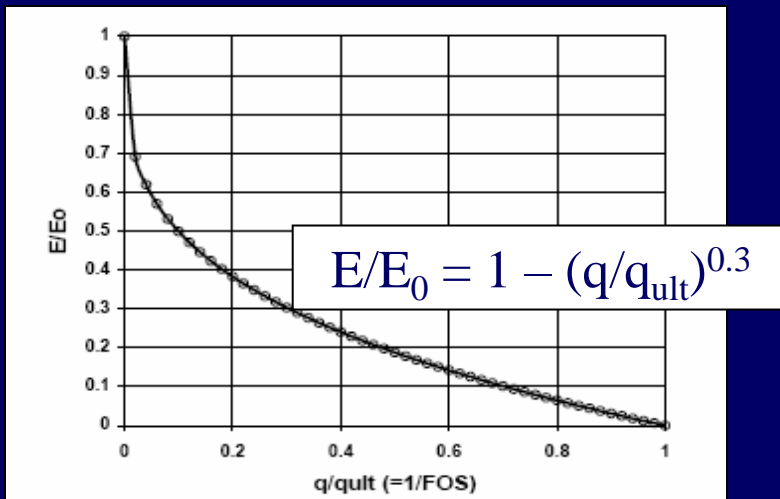
- $G_{max} = (\gamma_T/9.8) (V_s^2)$
  - G_{max} is in units of kN/m^2
  - γ_T is in units of kN/m^3
  - v_s is in units of m/s
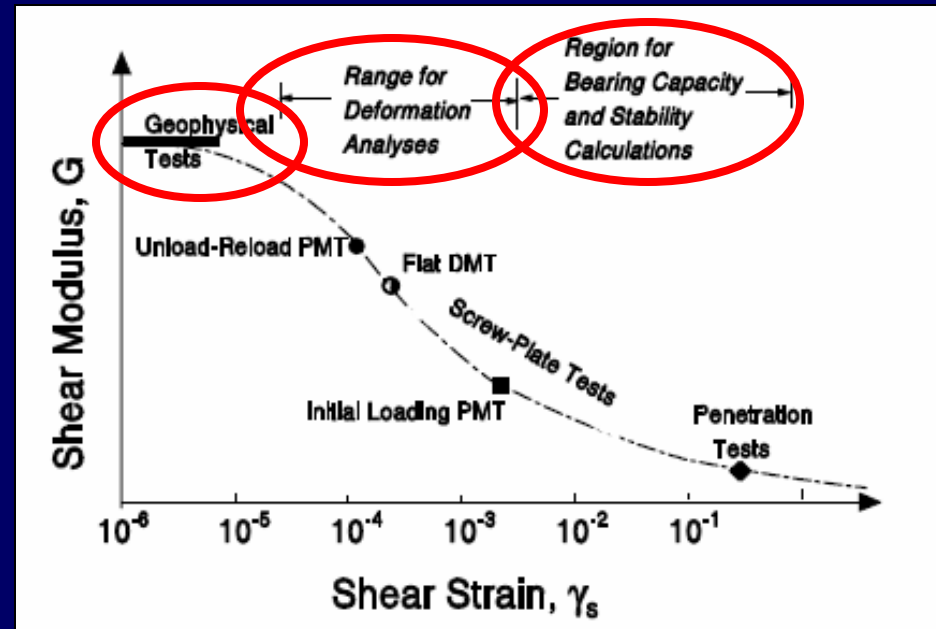
Soil Type	Small-strain shear modulus, G_o (kPa)
Soft clays	2,750 to 13,750
Firm clays	6,900 to 34,500
Silty sands	27,600 138,000
Dense sands and gravels	69,000 to 345,000

Estimation of the equivalent or initial Young's Modulus (E_0 or E_{max}) from the small-strain shear modulus (G_0 or G_{max})

- $E_0 = 2(G_0)(1 + \nu)$
    - $\nu = 0.2$ for drained conditions
    - $\nu = 0.5$ for undrained conditions
- The equivalent elastic modulus for larger strains is calculated as follows:
   - $E_s = (E/E_0)E_0$
    - $E_s = (1 - q/q_{ult})^{0.3}(E_0)$

$$E/E_0 = 1 - (q/q_{ult})^{0.3}$$

Soil Type		Range of Equivalent Elastic Modulus (kPa)
Clay		
	Soft sensitive	2,500 to 15,000
	Medium stiff	15,000 to 50,000
	Very stiff	50,000 to 100,000
Loess		15,000 to 60,000
Silt		2,000 to 20,000
Fine sand		
	Loose	8,000 to 12,000
	Medium dense	12,000 to 20,000
	Dense	20,000 to 30,000
Sand		
	Loose	10,000 to 30,000
	Medium dense	30,000 to 50,000
	Dense	50,000 to 80,000
Gravel		
	Loose	30,000 to 80,000
	Medium dense	80,000 to 100,000
	Dense	100,000 to 200,000

Estimating the <u>drained</u> soil stiffnesses, D' and E', from cone tip data (Mayne 2006)
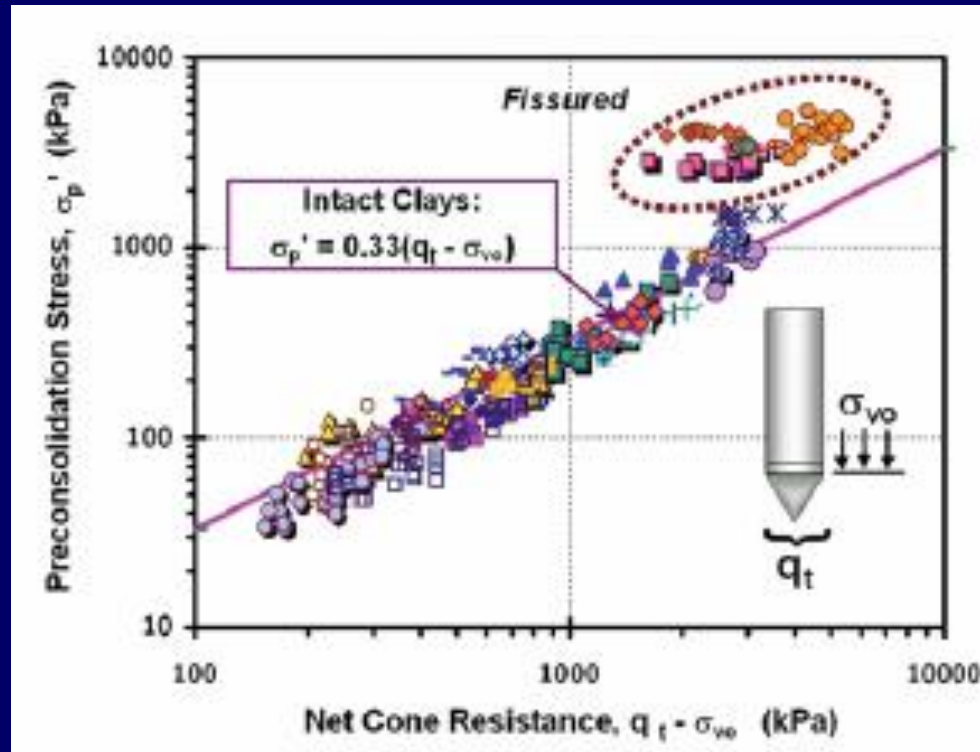
- D' is the constrained modulus for drained loading.
- $D' = \alpha_c' (q_t - \sigma_{v0})$
  - where $\alpha_c' = 5$ for normally consolidated clean sands, silts and intact clays (not for organic clays or cemented sands)
- E' is the Young's modulus for drained loading.
- $E' = D' ((1 + \nu') (1 - 2(\nu'))/(1 - \nu')$
  - assume $\nu' = 0.2$ for drained conditions

However, it is recommended that soil stiffness be estimated with G_{max} correlations because q_t is a measure of soil strength, not stiffness. The relationship between D' and q_t is to be considered suspect at this time.
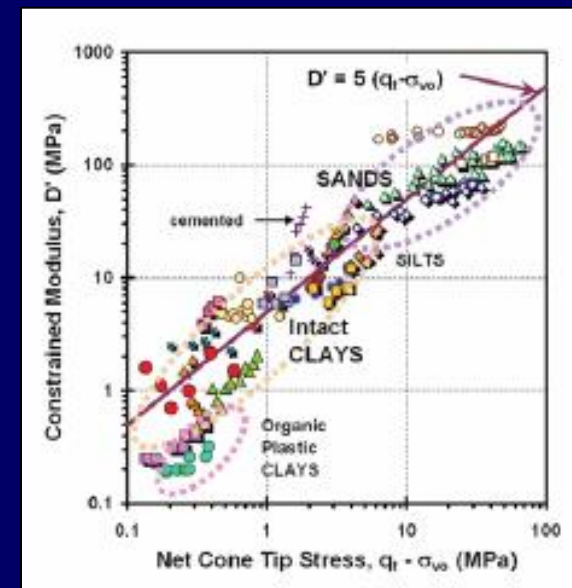
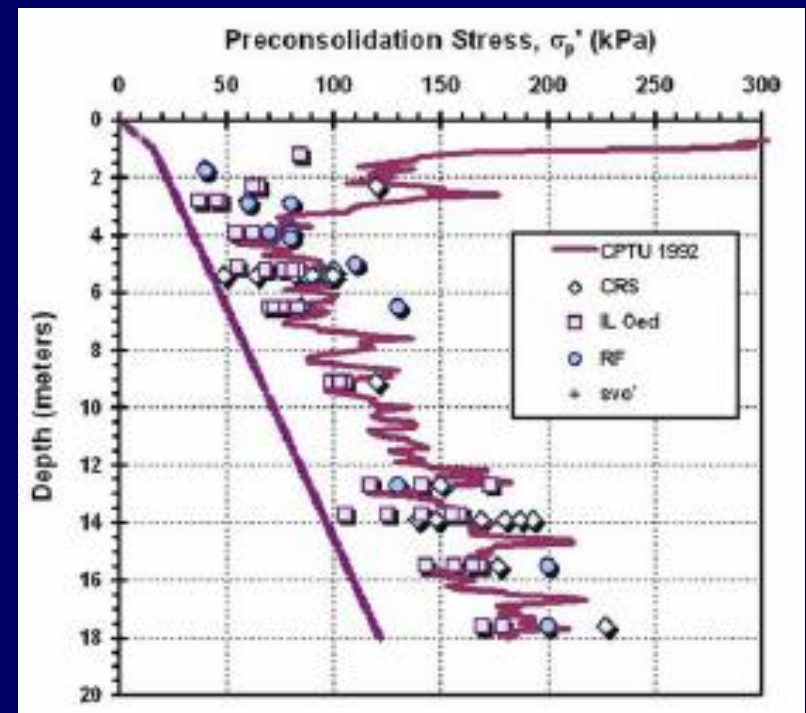# Estimating the preconsolidation stress ($\sigma_p{}'$) of intact clays from the net cone tip resistance
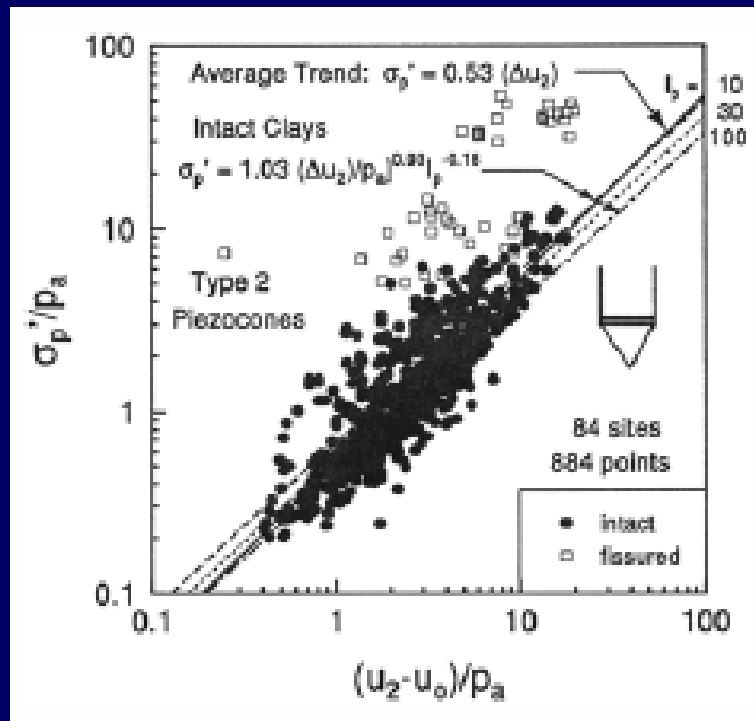
$$\sigma_p{}' = 0.33\,(q_t - \sigma_{vo})$$

Estimating the preconsolidation stress (σ_p') of intact clay from pore pressure data

$$\sigma_p' = 0.53 \, (u_2 - u_0)$$

$$\sigma_p' = 0.60 \, (q_t - u_2)$$

This approach can <u>not</u> be used for clays that dilate and u_2 is <u>negative</u>.

Estimating the preconsolidation stress (σ_p') of normally to over consolidated sand from the cone tip resistance data and the friction angle

$$\sigma_p' = (\sigma_{vo}') (A/B)^{(1/(\sin \phi' - 0.27))}$$
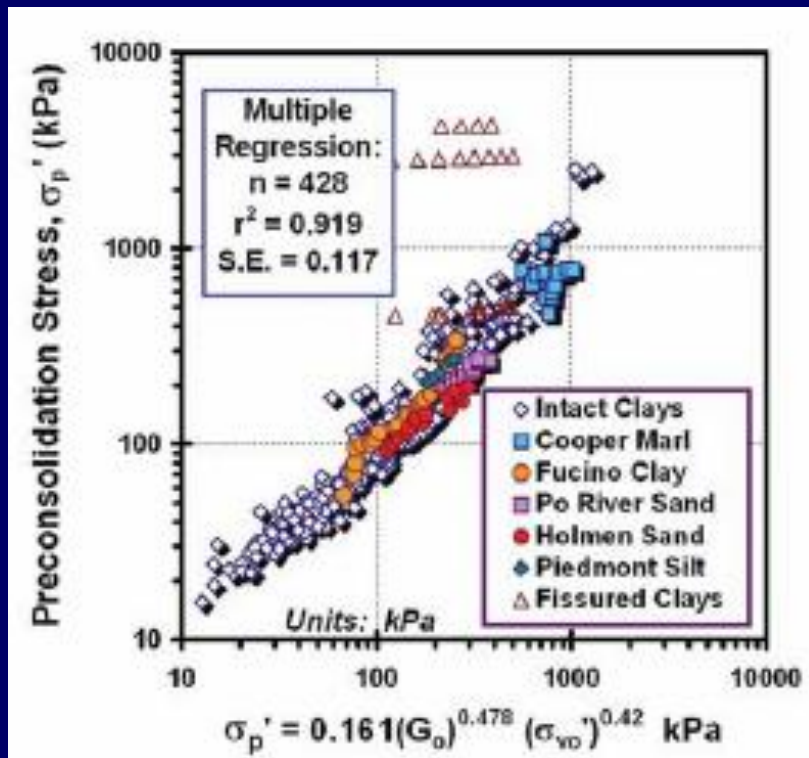
$$A = (0.192) (q_t / \sigma_{atm})^{0.22}$$

$$B = (1-\sin \phi') (\sigma_{vo}'/\sigma_{atm})^{0.31}$$

where $\phi' = (17.6 + (11.0) (\log (((q_t/\sigma_{atm})/(\sigma_{vo}'/\sigma_{atm}))^{0.5}))$
and $\sigma_{atm} = 100 \text{ kPa} = 1 \text{ TSF}$

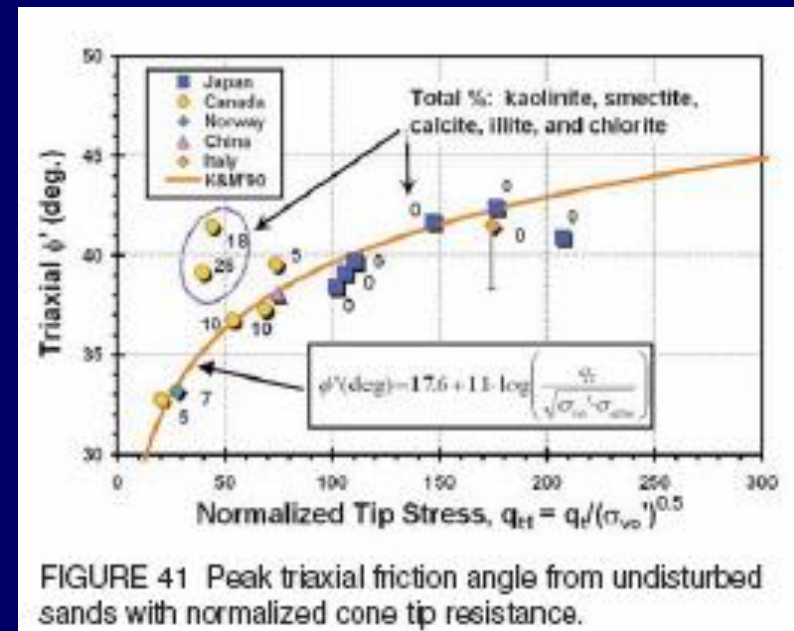# Estimating the preconsolidation stress (σ_p') of mixed soils from the small strain shear modulus

$$\sigma_p' = 0.101 \, (\sigma_{atm}^{0.102}) \, (G_0^{0.478}) \, ((\sigma_{v0}')^{0.420})$$

where $G_0 = (\gamma_T/9.8) \, (V_s^2)$
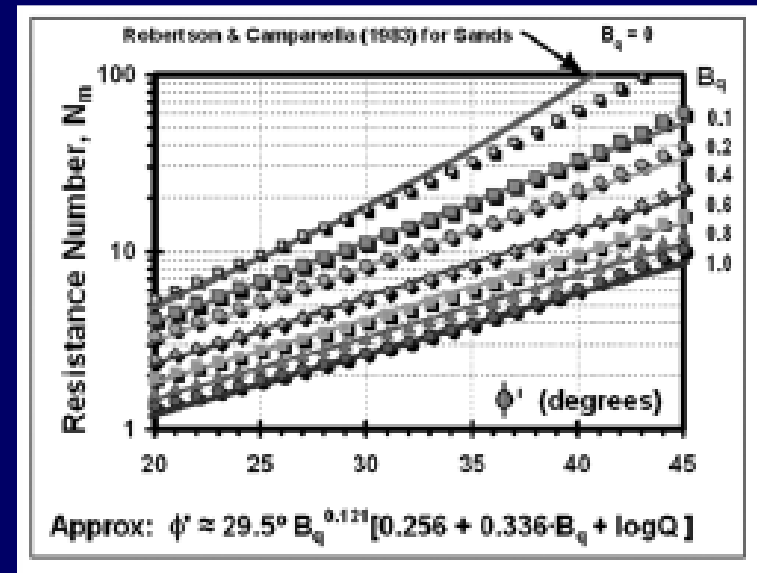and $\sigma_{atm} = 100 \text{ kPa} = 1 \text{ TSF}$

Estimating the effective friction angle (ϕ') of clean sand from cone tip resistance data (Kulhawy and Mayne, 1990)

- $\phi' = 17.6 + (11.0) \left(\log \left(\left((q_t/\sigma_{atm})/(\sigma_{vo}'/\sigma_{atm}) \right)^{0.5} \right) \right)$
  - ϕ' is in units of degrees
  - q_t, σ_{atm} and σ_{vo}' are in the same units of stress
  - applies when $B_q < 0.1$
    - $B_q = (u_2 - u_0)/(q_t - \sigma_{vo})$

FIGURE 41 Peak triaxial friction angle from undisturbed sands with normalized cone tip resistance.

Estimating the effective friction angle (ϕ') of mixed soil types with net tip resistance and pore pressure data (Senneset et al., 1988, 1989)

- $\phi' = 29.5\,(B_q)^{0.121}\,(0.256 + 0.336\,(B_q) + \log(Q))$
  - ϕ' is in units of degrees
  - Applies to $20 < \phi' < 45$ degrees
  - applies when $0.1 < B_q < 1.0$
    - $B_q = (u_2 - u_0)/(q_t - \sigma_{vo})$
    - $Q = (q_t - \sigma_{vo})/\sigma_{v0}'$

Robertson & Campanella (1983) for Sands $B_q = 0$

Resistance Number, N_m

ϕ' (degrees)

Approx: $\phi' \approx 29.5^\circ\,B_q^{0.121}[0.256 + 0.336 \cdot B_q + \log Q]$

Estimating the undrained shear strength (s_u) of clays from the preconsolidation stress (σ_p')

$$s_u = 0.22\,(\sigma_p')$$

- For OCR < 2
- Based on vane shear tests and back analysis from failures for embankments, footings and excavations.
- Fissured clays can exhibit s_u values 50% of the s_u of non-fissured clays. Fissured clays can be identified by the negative pore pressures during penetration.

Estimating the undrained shear strength (s_u) of clays from correlation with local experience

$$s_u = (q_t - \sigma_{v0})/N_{kt}$$

- N_{kt} is determined from local experience.

- N_{kt} is correlated to specific lab or field undrained shear strength test methods.

Estimating the sensitivity of soft clays

- For low OC clays, OCR < 2
- The friction sleeve measurement is regarded as an indication of the remolded shear strength.
  - $f_s = s_{ur}$
- Combining this formula with two of the previously presented relationships:
  - $\sigma_p' = 0.33\,(q_t - \sigma_{vo})$
 - $s_u = 0.22\,(\sigma_p')$

$$S_t = 0.073\,(q_t - \sigma_{vo})/f_s$$

Estimating the relative density (D_R) of relatively clean sand from tip resistance data (Jamiolkowski et al., 2001)

- $D_R = (100)((0.268)((\ln((q_t/\sigma_{atm})/(\sigma_{vo}'/\sigma_{atm})^{0.5}) - 0.675))$
  - q_t, σ_{atm} and σ_{vo}' are in the same units of stress
  - This formula applies to medium compressibility sands.
  - Carbonate sands are high compressibility.
  - D_r can be used to determine ϕ' with the same correlations that are commonly used with SPT data.
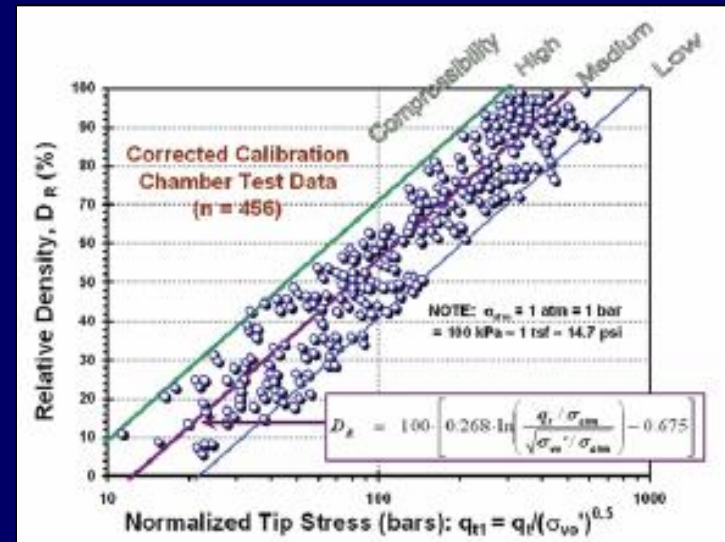
Estimation of the coefficient of consolidation (c_{vh}) from pore pressure dissipation data and the rigidity index (Teh and Houlsby, 1991))

- Based on the strain path method (SPM).
- $c_{vh} = ((T_{50}) (a_c) (I_R)^{0.5})/t_{50}$
  - $T_{50} = 0.245$ for a 15 cm^2 cone tip
  - $a_c = 2.2$ cm for a 15 cm^2 cone tip
  - t_{50} is the observed time for dissipation of 50% Δu
  - I_R determination is on the next page
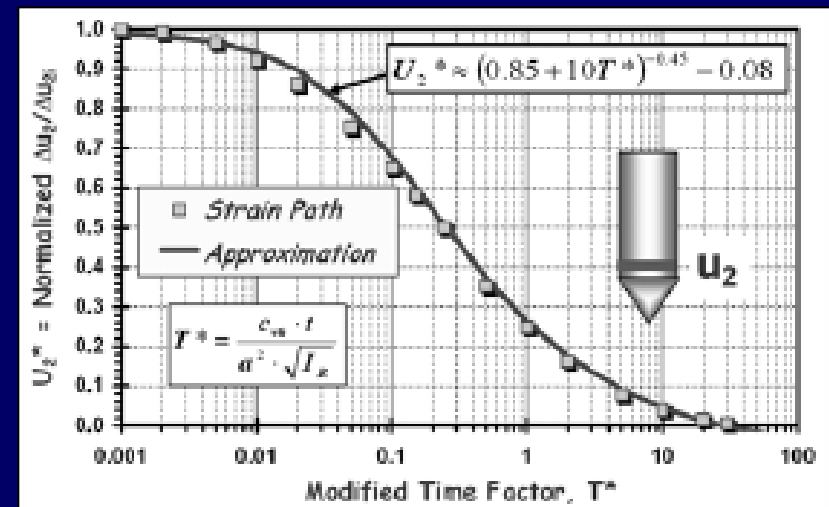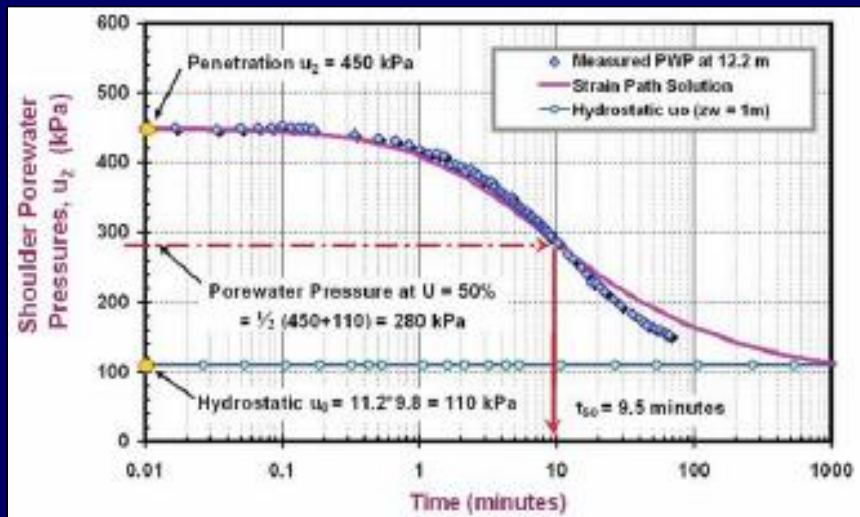
Estimation of the rigidity index (I_R) for clays and silts with net tip resistance and the pore pressure data (Mayne, 2001)
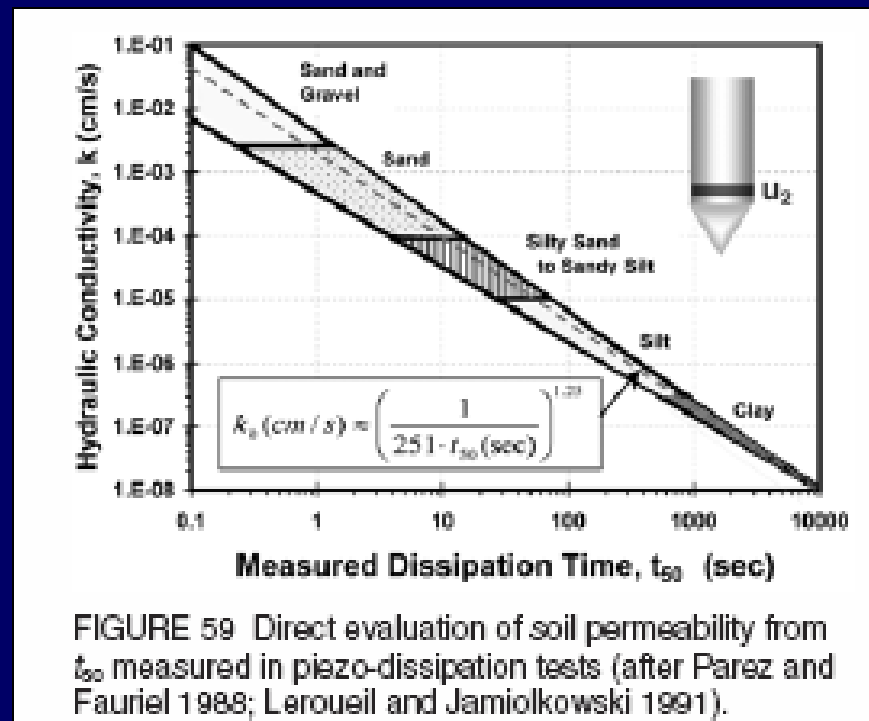
- $I_R = G/s_u$
- I_R is used to calculate c_{vh}.
- $I_R = \exp(((1.5/M) + 2.925)((q_t - \sigma_{vo})/(q_t - u_2)) - 2.95)$
  - where $M = 6(\sin \phi')/(3 - \sin \phi')$

If plasticity index and OCR are known, this empirical correlation can be used.
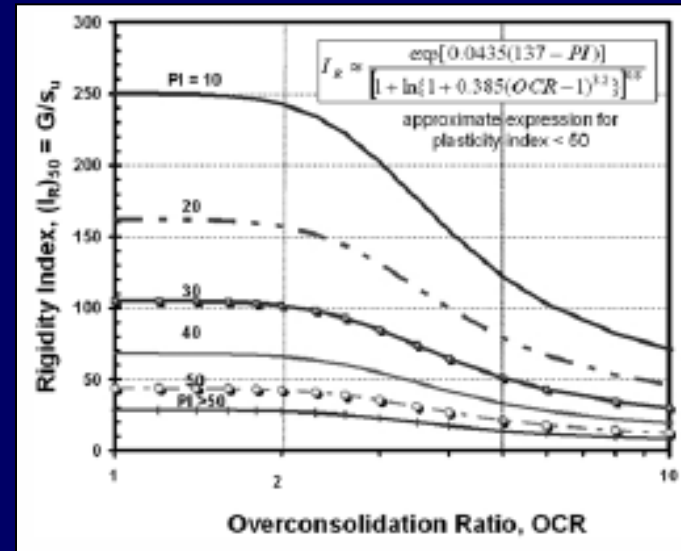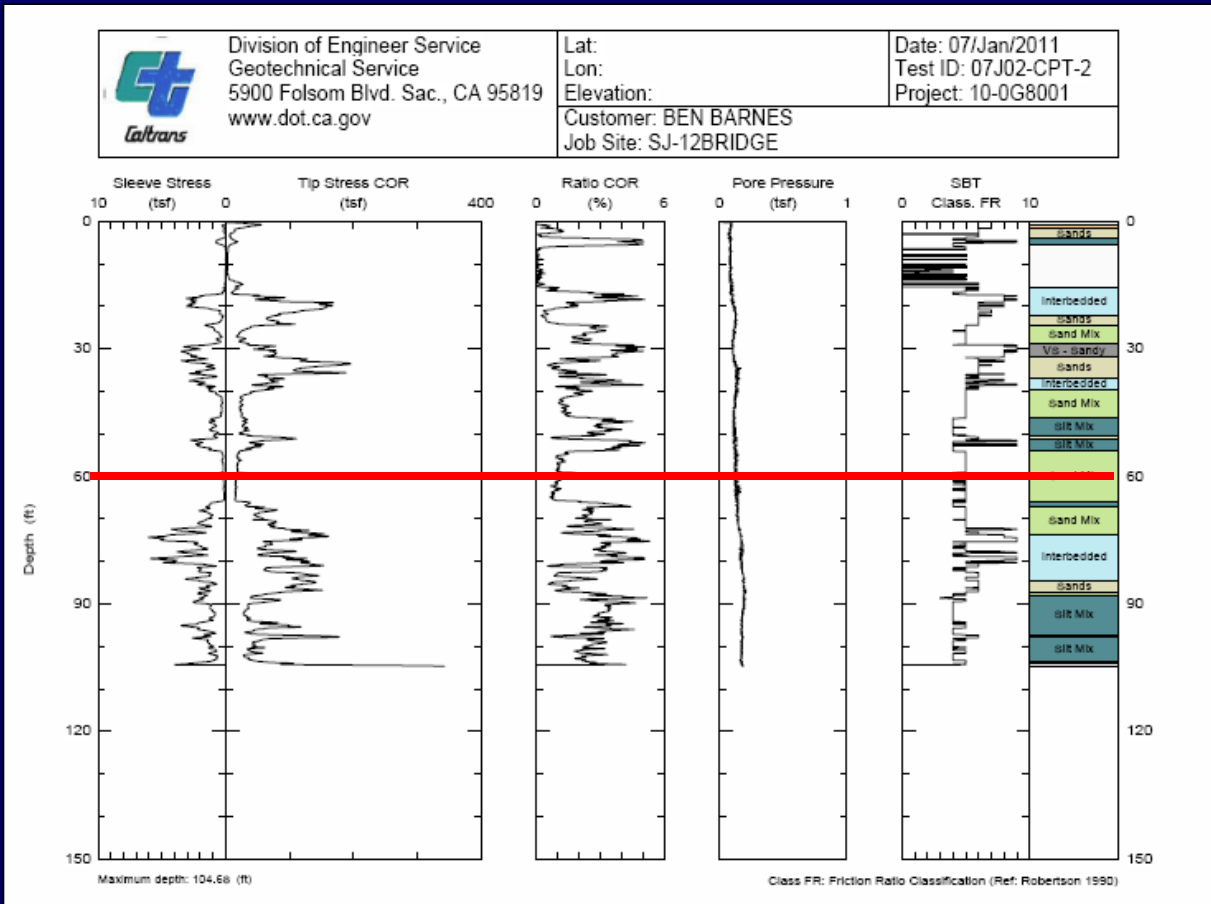
Estimation of the horizontal coefficient of hydraulic conductivity (k_h) from the observed t_{50} (Parez and Fauriel, 1988)

- The trend line can be used to estimate k_h.

- The k_h value may be useful for the design of ground improvement strategies, such as wick drains.

FIGURE 59 Direct evaluation of soil permeability from t_{50} measured in piezo-dissipation tests (after Parez and Fauriel 1988; Leroueil and Jamiolkowski 1991).

Calculate the engineering properties of cohesionless soil from CPT data

- depth = 60 feet = 18.3 m
- q_t = 18 TSF = 1.8 MPa
- f_s = 0.21 TSF = 21 kPa
- $\sigma_{v0} = \sigma_{v0}' = 3.6$ TSF = 0.36 MPa
- u_2 = 0 TSF = 0 MPa
- u_0 = 0 TSF = 0 MPa

Calculate the engineering properties of cohesionless soil from CPT data

Shear wave velocity, v_s (Baldi)

$V_s = 277 \, (q_t)^{0.13} \, (\sigma_{v0}')^{0.27}$

$V_s = 277 \, (18)^{0.13} \, (0.36)^{0.27}$

$V_s = 156$ m/sec

Total unit weight from v_s

$\gamma_T = 8.32 \, (\log V_s) - (1.61) \, (\log z)$

$\gamma_T = 8.32 \, (\log 166) - (1.61) \, (\log 18.3)$

$\gamma_T = 18.5 - 2.0 = 16.5$ kN/m^3 = 105 pcf

Shear wave velocity, v_s (Hegazy, Mayne)

$V_s = ((10.1) \, (\log q_t) - 11.4))^{1.67} \, ((f_s/q_t) \, (100))^{0.3}$

$V_s = ((10.1) \, (\log 1800) - 11.4))^{1.67} \, ((21/1800) \, (100))^{0.3}$

$V_s = 167.7 \, (1.05) = 176$ m/sec

Total unit weight from f_s

$\gamma_{sat} = 2.6 \, (\log f_s) + 13.25$

$\gamma_{sat} = 2.6 \, (\log 21) + 13.25$

$\gamma_{sat} = 16.7$ kN/m^3 = 106 pcf

Small strain shear modulus

$G_{max} = (\gamma_T/9.8) \, (V_s^2)$

$G_{max} = (16.6/9.8) \, (166^2)$

$G_{max} = 46{,}700$ kPa

Calculate the engineering properties of cohesionless soil from CPT data

Drained equivalent Young's modulus

$E_0 = 2(G_0)(1 + \nu)$

$E_0 = 2(46,700)(1 + 0.2)$

$E_0 = 112,000$ kPa

Relative density

$D_R = (100)((0.268)((\ln((q_t/\sigma_{atm})/(\sigma_{vo}'/\sigma_{atm})^{0.5}) - 0.675))$

$D_R = (100)((0.268)((\ln((18/1.0)/(3.6/1.0)^{0.5}) - 0.675))$
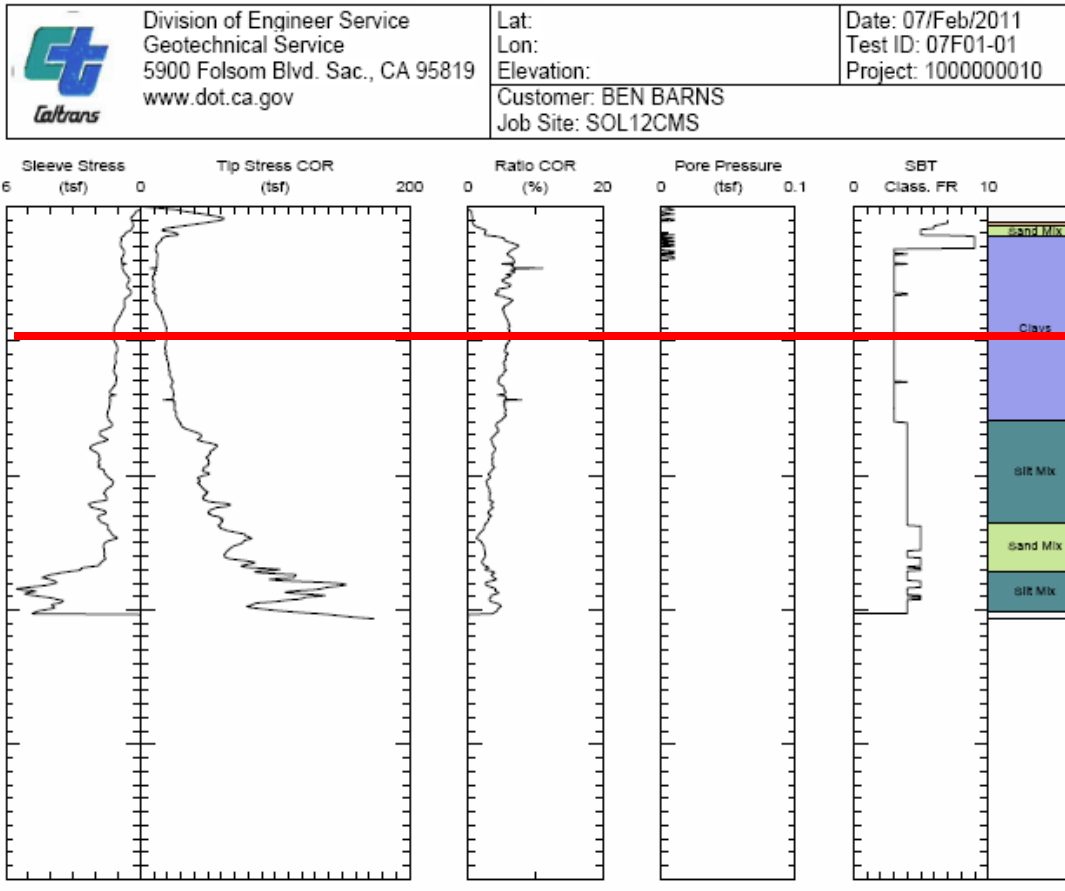
$D_R = (100)((0.268)((2.25) - 0.675))$

$D_R = 42$ %

Friction angle

$\phi' = 17.6 + (11.0)(\log(((q_t/\sigma_{atm})/(\sigma_{vo}'/\sigma_{atm}))^{0.5}))$

$\phi' = 17.6 + (11.0)(\log(((18/1.0)/(3.6/1.0))^{0.5}))$

$\phi' = 28$ degrees

Calculate the engineering properties of cohesive soil from CPT data

- depth = 10 feet = 3.28 m
- q_t = 19 TSF = 1.9 MPa
- f_s = 1.15 TSF = 115 kPa
- $\sigma_{v0} = \sigma_{v0}' = 0.5$ TSF= 0.05 MPa
- u_2 = 0 TSF = 0 MPa
- u_0 = 0 TSF = 0 MPa

Calculate the engineering properties of cohesive soil from CPT data

Shear wave velocity, v_s (Mayne)

$V_s = 1.75 \, (q_t)^{0.627}$

$V_s = 1.75 \, (1900)^{0.627}$

$V_s = 199 \text{ m/sec}$

Total unit weight from v_s

$\gamma_T = 8.32 \, (\log V_s) - (1.61) \, (\log z)$

$\gamma_T = 8.32 \, (\log 247) - (1.61) \, (\log 3.28)$

$\gamma_T = 19.9 - 0.8 = 19.1 \text{ kN/m}^3 = 121 \text{ pcf}$

Shear wave velocity, v_s (Hegazy, Mayne)

$V_s = ((10.1) \, (\log q_t) - 11.4)^{1.67} \, ((f_s/q_t) \, (100))^{0.3}$

$V_s = ((10.1) \, (\log 1900) - 11.4)^{1.67} \, ((115/1900) \, (100))^{0.3}$

$V_s = 170.8 \, (1.72) = 294 \text{ m/sec}$

Total unit weight from f_s

$\gamma_{sat} = 2.6 \, (\log f_s) + 13.25$

$\gamma_{sat} = 2.6 \, (\log 115) + 13.25$

$\gamma_{sat} = 18.6 \text{ kN/m}^3 = 118 \text{ pcf}$

Small strain shear modulus

$G_{max} = (\gamma_T/9.8) \, (V_s^2)$

$G_{max} = (18.9/9.8) \, (247^2)$

$G_{max} = 117,700 \text{ kPa}$

Calculate the engineering properties of cohesive soil from CPT data

Drained equivalent Young's modulus
$E_0 = 2(G_0)(1 + \nu)$
$E_0 = 2(117,700)(1 + 0.2)$
$E_0 = 282,000$ kPa

Effective preconsolidation stress
$\sigma_p' = 0.33(q_t - \sigma_{vo})$
$\sigma_p' = 0.33(1.9 - 0.05)$
$\sigma_p' = 0.61$ MPa $= 610$ kPa $= 12.2$ ksf

Undrained shear strength
$s_u = 0.22(12.2)$
$s_u = 2.7$ ksf

Questions?